S282 Astronomy

Observing the energetic Universe

Study time: 1 hour

Summary

This web-based activity has three parts. In the first you will answer some questions about X-ray astronomy using the website devoted to the Chandra X-ray observatory. Following this you will compare two X-ray observatories – Chandra and XMM-Newton. Finally, you will use images taken with these observatories to explore the findings that link pulsars to supernova remnants.

This activity will require you to connect to the Internet for the whole session – about an hour.

You should have read to the end of Section 9.5 of *An Introduction to the Sun and Stars* before starting this activity.

Learning outcomes

- Appreciate the importance of X-ray astronomy in understanding a wide variety of energetic processes in the Universe.
- Identify, compare, evaluate and synthesize information from web-based resources.

Background to the activity

Over the last 40 years or so X-ray astronomy has been developed into an extremely important window on the Universe. This has been marked by the award of the Nobel Prize for Physics for 2002 to Riccardo Giacconi, one of the pioneers of the field. The technological development of this new area of astronomy has been extremely rapid and has greatly improved our understanding of some of the most energetic and violent processes in the Universe.

Question 1

(a) What are the typical wavelengths of X-rays?

(b) What are the typical photon energies of X-rays? Express your answer in electronvolts.

As you found in Question 1, the typical photon energies of X-rays are of order 10^3 eV. You will see that in X-ray astronomy it is common to describe photon energies in units of keV (1 keV = 10^3 eV).

Question 2

Calculate the temperature of an object that radiates with a black-body spectrum that peaks at a photon energy of 1 keV.

In this activity we will investigate the importance of X-ray astronomy in understanding a wide variety of energetic phenomena by considering two current generation X-ray satellites: Chandra and XMM-Newton.

Part 1 X-ray astronomy

- Start your web browser and connect to the Internet.
- Open the Chandra website (http://chandra.harvard.edu/). The first part of the activity will consist of answering a number of questions about X-ray astronomy using information that is provided on this website.
- Towards the top of the screen on the Chandra home page you should see a link called Field Guide. Follow this link and take a few minutes to see what sort of information is provided. Most of the information that you will need to answer Questions 3 to 5 can be found by following links from the Field Guide page.

Question 3

This question is about the information that X-rays can provide about stars and stellar remnants.

(a) Are X-rays produced in significant quantities by main sequence stars?

(b) Which types of stellar remnant are likely to produce X-rays? Under what circumstances are such objects very luminous X-ray sources?

Question 4

How can X-ray spectroscopy help us to determine the chemical composition of emitting regions?

Part 2 X-ray observatories

So far we have considered why we want to detect cosmic X-rays but not how such observations are made. In this part of the activity we will look at how X-ray astronomy is carried out.

- From the Chandra home page follow the link to Field Guide, and then study the links under the X-ray Astronomy heading. Spend a few minutes reading the information on these pages to get a feel for what is involved in making X-ray observations. In particular, you should study the X-ray Absorption page.

Consider the following in light of what you have read on these pages:

- ■ Why do we need to use a space-based telescope to detect cosmic X-rays?
- ❑ The Earth's atmosphere is opaque to X-rays and so our X-ray telescope must be taken above the bulk of the Earth's atmosphere.

In practice this means using a satellite, although early X-ray detectors were flown in sounding rockets and balloons. Rockets and balloons are still frequently used to test new types of X-ray telescope since the costs of launching a payload in this way are much less than a satellite launch, but the time above the atmosphere is very limited (minutes for a sounding rockets and days for a balloon).

Another aspect of X-ray astronomy that distinguishes it from optical astronomy relates to the techniques used to collect and focus X-rays.

- From the Chandra home page follow the link to Field Guide and then to History of X-ray Astronomy. Read the information about the history of X-ray astronomy, and then attempt the following question.

Question 5

Briefly describe how an X-ray telescope focuses X-rays.

At present there are two major X-ray satellites in operation with good imaging characteristics – Chandra (operated by NASA) and XMM-Newton (operated by the European Space Agency). In some ways these are similar instruments but in other ways their capabilities complement one another. In the next question you will use the Chandra and XMM-Newton websites to compare these two instruments.

- For this exercise it is probably best to use two browser windows for ease of comparison.
- From the Chandra website select the About Chandra link from the top of the screen.
- Open a new browser window (press Ctrl-N to open another window) and go to the XMM-Newton home page (http://sci.esa.int/xmm/).

Question 6

(a) Navigate around the Chandra and XMM-Newton websites to find the information required to complete Table 1.

(b) Using the information that you obtained in part (a) describe the aspects of Chandra and XMM-Newton that are similar, and those that are substantially different.

(c) Which observatory would be best suited to: (i) making detailed images of X-ray emitting sources, and (ii) observing the X-ray spectrum of faint sources?

Table 1 Information about the Chandra and XMM-Newton X-ray telescopes (for use with Question 4).

Feature of telescope	**Chandra**	**XMM-Newton**
Focal length/m	10	
Angular resolution/arcsec		
Collecting area (at a photon energy of about 1 keV)/cm^2		
Range of photon energies that can be detected/keV		

Both observatories have a number of instrument packages that can be used with the respective telescopes. There are two main types of instrument that are employed on both – imaging cameras and spectrometers. Chandra employs the High Resolution Camera (HRC) while XMM-Newton uses the European Photon Imaging Camera (EPIC).

Question 7

What is the essential difference between the imaging cameras on the two observatories?

Part 3 Pulsars and supernova remnants

One of the major achievements of the Chandra mission has been to help make the link between pulsars and supernova remnants. Although our ideas about pulsars suggest that these objects should be born in supernovae, before the arrival of Chandra there was little direct evidence for their unambiguous association. The Crab and Vela were the most obvious examples of pulsars associated with supernova remnants, but there were few others. There are two reasons for this:

1. The supernova is likely to 'kick' the pulsar away from the site of the explosion. Thus, only comparatively young pulsars are likely to be found within the supernova remnant.
2. Young supernova remnants and pulsars are not particularly luminous in the wavebands where imaging could be done efficiently pre-Chandra (e.g. optical, radio) since they are still at high temperatures. The good angular resolution of Chandra means that we can now take images in X-rays with high angular resolution to reveal the detailed structure of young supernova remnants.

In the final part of this activity you will use images taken with Chandra to show the association between pulsars and supernova remnants.

- Return to the Chandra home page and follow the links to Photo Album, Chandra Images by Category, e.g. Supernovas (or Supernovas & SNR) and Neutron Stars (or Neutron Stars/X-ray Binaries).

Question 8

The Crab Nebula surrounds the pulsar that remains from the supernova that produced it. Find two further associations between neutron stars and supernova remnants that have been observed by Chandra Are all of the X-ray sources that are thought to be neutron stars observed as pulsars?

Endnote

In this activity we have explored the importance of X-ray astronomy in telling us about energetic systems. We have also investigated the two premier X-ray observatories currently operating, including a brief look at how they compare. Finally, we looked at one of the questions that X-ray astronomy may be able to answer – how pulsars relate to the supernovae that formed them.

This completes our very quick tour of the energetic Universe using Chandra and XMM-Newton. Many of these topics are explored in much greater detail in the Open University Level 3 physics and astronomy courses.

Answers to questions

Question 1

(a) Figure 1.36 (of *An Introduction to the Sun and Stars*) shows that X-rays lie in the electromagnetic spectrum between the ultraviolet and γ-ray regions with wavelengths in the range 3×10^{-9} to 3×10^{-11} m.

(b) The energy of a photon is given by *An Introduction to the Sun and Stars*, Equation 1.3

$$E = hf$$

Where f is the frequency of the electromagnetic radiation and h is the Planck constant. The frequency of electromagnetic radiation is related to wavelength λ by *An Introduction to the Sun and Stars* Equation 1.2, which can be rearranged to give

$$f = c/\lambda$$

These two equations can be combined to give an equation for photon energy in terms of wavelength

$$E = hc/\lambda \qquad \text{(Equation A)}$$

Thus a photon with wavelength $\lambda = 3 \times 10^{-9}$ m has an energy of

$$E = (4.14 \times 10^{-15}\ \text{eV s}) \times (3.00 \times 10^{8}\ \text{m s}^{-1})/(3 \times 10^{-9}\ \text{m}) = 4 \times 10^{2}\ \text{eV}$$

and a photon with wavelength $\lambda = 3 \times 10^{-11}$ m has an energy of

$$E = (4.14 \times 10^{-15}\ \text{eV s}) \times (3.00 \times 10^{8}\ \text{m s}^{-1})/(3 \times 10^{-11}\ \text{m}) = 4 \times 10^{4}\ \text{eV}$$

(Note that we have used the value of $h = 4.14 \times 10^{-15}$ eV s, so that the photon energy will come out in units of electronvolts as required.)

So X-rays typically have photon energies between a few 10^2 eV and a few 10^4 eV.

Question 2

The first stage is to find the wavelength that corresponds to emission at a photon energy of 1 keV. Equation A from Question 1 provides a relationship between photon energy and wavelength

$$E = hc/\lambda \qquad \text{(Equation A)}$$

This can be rearranged to give

$$\lambda = hc/E$$

In this case, $E = 1 \times 10^{3}$ eV, (and remembering to use a value of h in appropriate units), so:

$$\lambda = (4.14 \times 10^{-15}\ \text{eV s}) \times (3.00 \times 10^{8}\ \text{m s}^{-1})/(1 \times 10^{3}\ \text{eV}) = 1.2 \times 10^{-9}\ \text{m}$$

To find the temperature of a black-body source that peaks at a given wavelength we need to use Wien's displacement law (*An Introduction to the Sun and Stars*, Equation 1.4)

$$(\lambda/\mathrm{m}) = \frac{2.90 \times 10^{-3}}{(T/\mathrm{K})}$$

which can be rearranged to give

$$(T/\mathrm{K}) = \frac{2.90 \times 10^{-3}}{(\lambda/\mathrm{m})}$$

So for a photon with a wavelength of 1.2×10^{-9} m

$$(T/\mathrm{K}) = \frac{2.90 \times 10^{-3}}{1.2 \times 10^{-9}} = 2.4 \times 10^{6}$$

So the black-body source that peaks at a photon energy of 1 keV has a temperature of 2×10^{6} K (to one significant figure).

Question 3

(a) The photospheres of main sequence stars typically have temperatures of a few times 10^3 K to a few times 10^4 K. We saw in Question 2 that X-rays are produced when matter is heated to $\sim 10^6$ K. This is a higher temperature than the photospheres of main sequence stars, so main sequence stars will not be copious producers of X-rays. Although the solar corona reaches temperatures of a few million K the X-ray luminosity produced is small because the corona is so diffuse. Similarly we would expect the emission from stellar coronae to be weak (see http://chandra.harvard.edu/xray_sources/normal_stars.html).

(b) The three types of stellar remnant that were introduced in Chapter 9 of *An Introduction to the Sun and Stars* are: white dwarfs, neutron stars and black holes. X-ray emission occurs in environments where the temperature is about 10^6 K. Typically such high temperatures are generated where high magnetic fields, extreme gravity or explosive forces occur. Stellar remnants can provide the conditions needed for X-ray emission.

Isolated white dwarfs have high surface temperatures and so may be sources of X-rays. However, such stars cool rapidly and do not remain as luminous X-ray sources for an appreciable time. Much more luminous X-ray sources are interacting binaries in which accretion occurs onto a white dwarf.

Some neutron stars are pulsars that are powered by the rotational energy of the star, and some of these are X-ray sources. Neutron stars may also exist in interacting binaries, and accretion onto a neutron star may result in a very luminous X-ray source.

Isolated black holes are not sources of X-ray emission, but interacting binaries in which accretion occurs onto a black hole are (like interacting neutron star binaries) strong X-ray sources.

In all three cases (white dwarf, neutron star and black hole) there is strong emission of X-rays in interacting binaries. Under such circumstances the X-ray emission can tell us something about the intense pressure and heating by compression and viscous (frictional) forces experienced by matter as it spirals into the stellar remnant. The brightest X-ray sources in our Galaxy are neutron stars and black holes and so X-rays provide an ideal tool for exploring these late stages of stellar evolution.

See also the following sites:

http://chandra.harvard.edu/xray_sources/white_dwarfs.html

http://chandra.harvard.edu/xray_sources/neutron_stars.html

http://chandra.harvard.edu/xray_sources/blackholes_stellar.html

Question 4

X-rays are also produced through emission and absorption by electrons bound in atoms. We have already seen (Section 1.3.2 of *An Introduction to the Sun and Stars*) that line spectra are produced when electrons change energy level in atoms; we have noted that the majority of such transitions are in the optical and UV regions of the spectra. However, in heavier atoms the innermost electrons are very tightly bound and transitions involving these electrons correspond to energies in the X-ray region. As with other spectral lines these transitions have characteristic energies that indicate which element is involved. Thus X-ray spectroscopy can identify the chemical composition of these very hot regions (see http://chandra.harvard.edu/xray_astro/xrays.html).

Question 5

X-rays cannot be focussed using the equivalent of lenses but instead a system of X-ray mirrors is used. This works because if X-rays strike a metal surface at a very small angle they will be reflected. By careful choice of the shape of these metal surfaces the X-rays can be focussed and an image formed. This type of X-ray telescope is known as a grazing incidence telescope (see http://chandra.harvard.edu/xray_astro/history.html).

Question 6

(a) A completed table of information about Chandra and XMM-Newton is given in Table 2.

Table 2 A summary of information about the Chandra and XMM-Newton X-ray telescopes.

Feature of telescope	Chandra	XMM-Newton
Focal length/m	10	7.5
Angular resolution/arcsec	0.5	5
Collecting area (at a photon energy of about 1 keV)/cm^2	400	4300
Range of photon energies that can be detected/keV	0.09–10	0.1–12

Note that the details for Chandra can be found in the 'Chandra Specifications handout' available from the observatory's website. To access this information go to the About Chandra page of the site, click on Chandra Hardware in the left-hand menu and then follow this menu down to the bottom of the page. Here you will see a links to HTML and PDF versions of the handout.

The corresponding values for XMM-Newton can be found from the Fact Sheet link, which can be found on the menu on the left-hand side of the XMM-Newton home page.

(b) Both telescopes have similar focal lengths and operate over similar ranges of photon energy. The angular resolution of Chandra is about a factor of 10 better than that of XMM-Newton. However, the collecting area of XMM-Newton is more than a factor of 10 greater than that of Chandra.

(c) Since Chandra has the better angular resolution it would be better suited to making detailed images of X-ray emitting regions. The spectrum of a faint X-ray source would be better obtained using XMM-Newton since it has a larger collecting area than Chandra.

Question 7

The main difference is the technology used to detect the imaged X-rays. The EPIC imaging device on XMM-Newton uses charge-coupled devices (CCDs) that are essentially similar to the chips used in ordinary digital cameras (see the Instruments link on the menu on the left-hand side of the XMM-Newton home page). The main imaging instrument on Chandra is the High Resolution Camera (HRC). This instrument uses devices called micro-channel plates, which have higher spatial resolution than CCDs and so match the imaging capability of its telescope (see the Science Instruments link on the left of the About Chandra web page). High-energy X-ray photons liberate electrons from the front of a micro-channel plate. The electrons are accelerated along collimated channels to generate a signal from which the arrival directions and energies of the original X-ray photons can be measured.

Question 8

This is a very rapidly moving field and it is quite likely that more information has been added to the website in the time between this activity being written and the time you are doing it. At the time of writing, the situation was as follows.

Evidence for the association takes the form of a point-like source towards the centre of a young supernova remnant. Apart from the Crab and Vela, examples now include the following supernova remnants: G54.1+0.3, B1509–58, G292.0+1.8, E0102–72.3 (also referred to as E0102–72 on the Chandra website), G21.5–0.9 3C58, G11.2–0.3, IC 443, PSR 0540–69, Cas A (possibly), G320.4–1.2, and the pulsar B1509–58 in supernova remnant G320.4–1.2.

Not all of these sources are pulsars – some do not show any pulses. The non-pulsing sources mentioned on these pages are: Cas A, IC 443, G21.5–0.9.

Resources

Chandra home page http://chandra.harvard.edu/

XMM-Newton home page http://sci.esa.int/xmm/

Website addresses for specific pages within these sites are given in the answers to various questions.